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WAVE VELOCITIES IN THE EARTH'S CORE

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ABSTRACT

More than 700 seismograms of 39 shocks recorded mainly in southern California at epicentral distances between 105 and 140 degrees are used to investigate records of phases which have penetrated the earth's core. Properties of PKIKP, SKP, SKIKP, PKS, and PKIKS are discussed. Portions of travel-time curves of these phases are revised. Travel times of waves starting and ending at the surface of the core, and wave velocities in the core, are recalculated. Between about 1,500 and 1,200 km. from the earth's center in the transition zone from the liquid outer to the probably solid inner core, waves having lengths of the order of 10 km. travel faster than longer waves. This is probably caused by a rather rapid increase in viscosity toward the earth's center in this transition zone.

MATERIALS

THE PRESENT reinvestigation of properties and travel times of PKIKP,[1] SKIKP, SKP, PKIKS, and PKS is based mainly on a study of seismograms of 39 shocks (table 1) recorded at stations of the Pasadena network in southern California, at Tucson in Arizona, Boulder City and Nelson in Nevada (records of these 3 stations kindly supplied by the U. S. Coast and Geodetic Survey), and, in addition, for one shock (April 16, 1957), at Seattle, Washington (courtesy Mr. F. Neumann), Berkeley and Lick, California (courtesy Dr. P. Byerly), and at Palisades, New York (courtesy Dr. M. Ewing). Arrival times of apparent onsets of phases have been determined from the beginning of the seismograms to the portion preceding PPP. Moreover, records of one earthquake (August 9, 1956, 23:00:46, 16° S 175° W, focal depth 270 km.) written at Uppsala, Kiruna, and Skalstugan have been kindly supplied by Dr. M. Båth.

All stations in and near California are equipped at least with a short-period Benioff vertical seismograph. At Pasadena, Barrett, Tinemaha, Riverside, and Tucson, long-period Benioff vertical and horizontal seismographs were recording at least part of the time, and, in addition, short-period horizontal Benioff seismographs are operated at Pasadena, Boulder City, and Tucson. During parts of 1956 and 1957, long-period Press-Ewing vertical and horizontal seismographs were recording at Pasadena. Characteristic magnifications of some instruments at Pasadena are listed in table 2. For a given type of instrument the forms of the magnification curves are similar at all stations, but the magnifications of the systems differ.

Epicenter, origin time, and focal depth have been determined for each shock by

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[1] In the present paper, "K" refers to the outer core only, "I" to the inner core.

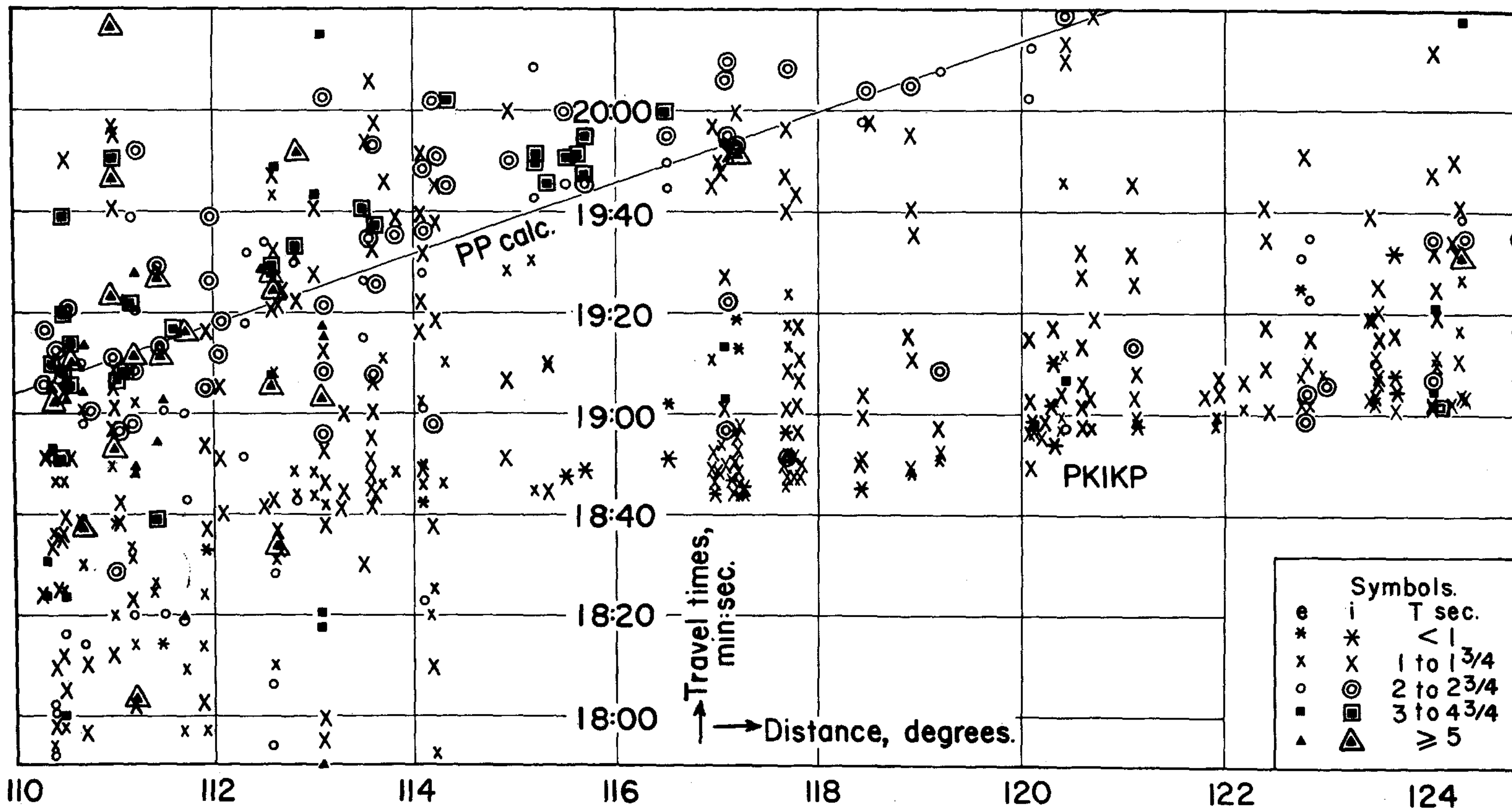

Fig. 1. Travel times observed in shallow shocks of table 1 at distances between 110° and 125°.

TABLE 1
LIST OF SEISMOGRAMS WHICH HAVE BEEN MEASURED

Date	Origin time	Focal depth	Epicenter		No. of stations	No. of seismograms	Range of distances
			Lat.	Long.			
	h. m. s.	km.	deg.	deg.			deg.
1952, Aug. 17.....	16:02:07	s[a]	30½ N	91½ E	7	9	107–114
1953, Apr. 6.....	00:36:13	s	7 S	131½ E	8	13	110–117
June 25.....	10:43:57	s	8¾ S	147 E	9	11	117–124
June 25.....	10:45:00	s	8¾ S	147 E	9	14	117–124
June 26.....	05:42:54	50±	8¾ S	147 E	9	12	117–124
1954, Jan. 1.....	13:04:18	100	9 S	123½ E	12	17	118–125
Feb. 20.....	18:35:05	580	6¾ S	124½ E	12	20	115–123
Feb. 22.....	12:03:26	140	57 S	26½ W	10	18	113–121
Mar. 21.....	23:42:11	180	24½ N	95½ E	12	21	111–118
Mar. 31.....	18:25:47	s	12½ N	58 E	12	25	130–135
1954, May 31.....	15:48:48	150	8 S	118½ E	9	13	121–128
July 3.....	22:31:26	80	6½ S	105¼ E	10	22	130–138
Oct. 21.....	00:10:07	s	41 S	80½ E	11	17	163–168
Nov. 2.....	08:24:10	s	7½ S	119 E	10	15	120–128
1955, Mar. 22.....	14:05:05	s	8½ S	92 E	11	21	140–148
Mar. 31.....	18:17:03	s	8 N	124 E	11	16	106–114
May 17.....	14:49:50	s	7 N	94 E	11	20	126–134
Sept. 23.....	15:06:19	s	26¾ N	101¾ E	9	13	106–114
Oct. 21.....	23:09:40	s	¾ S	123½ E	10	15	112–120
1956, Apr. 10.....	13:16:08	140	2 S	102 E	9	21	129–137
June 9.....	23:13:52	s	35 N	67½ E	12	24	108–113
July 16.....	15:07:07	s	22¼ N	96 E	11	16	113–120
July 18.....	06:19:35	190	5½ S	130 E	11	25	110–118
Nov. 13.....	09:55:30	s	48½ S	123½ E	10	14	132–137
1957, Feb. 10.....	22:32:15	s	10 N	126 E	9	16	103–107
Feb. 11.....	01:14:44	s	10 N	126 E	10	17	103–107
Mar. 23.....	05:12:40	150±	5½ S	131 E	12	27	109–117
Apr. 14.....	07:11:50	s	31½ N	85 E	9	13	108–113
Apr. 16.....	04:04:05	600	4¾ S	107 E	18[b]	34	119–144
1957, Apr. 24.....	19:10:05	s	36½ N	28 E	7	13	100–104
Apr. 25.....	02:25:36	s	36½ N	28 E	7	13	100–104
Apr. 28.....	01:23:40	s	7½ N	126¾ E	10	15	104–113
June 10.....	00:59:54	s	10 S	117 E	10	21	123–131
June 18.....	02:12:12	s	14½ N	96 E	8	14	120–127
1957, June 22.....	23:50:23	s	1½ S	137 E	8	19	101–110
July 2.....	00:42:23	s	35¾ N	52¾ E	9	25	107–111
July 9.....	09:58:09	40	6 S	103¾ E	11	23	131–139
Sept. 24.....	08:21:05	s	5½ N	128 E	9	19	104–108
Dec. 13.....	01:44:59	s	34½ N	48 E	13	27	107–112
Total...........	....	.....	....	....	395	708	....

[a] s indicates "shallow" depth.
[b] Plus reports of 18 stations, range of distances 122° to 144°.

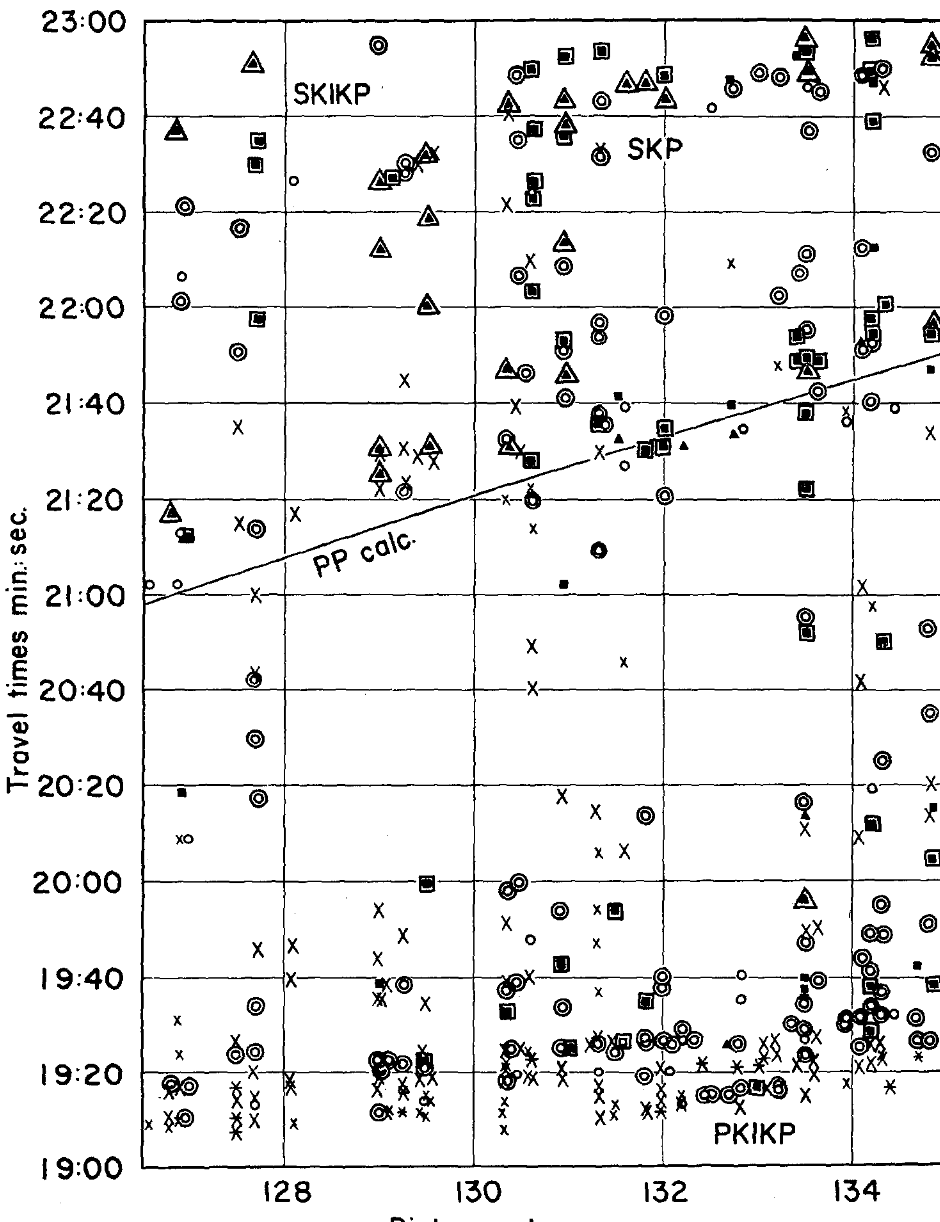

Fig. 2. Travel times observed in shallow shocks of table 1 at distances between 126½° and 135°. Symbols as in figure 1.

use of station bulletins, and geocentric distances have been calculated to the stations for which seismograms have been measured. The resulting travel times have been plotted separately for each of the 39 shocks. Later, the observed travel times for all shallow shocks have been combined in one graph, portions of which are reproduced in figures 1 and 2.[2] Standard travel times for PP (which was not investigated in detail) have been added for reference on all graphs. Figure 3 gives an example of travel times found for a deep-focus shock. Finally, travel-time curves determined for the combined shallow shocks, and the corresponding curves for individual deep shocks have been reduced to zero depth by use of depth corrections given by Jeffreys-Bullen (1940) and by Gutenberg and Richter (1936), and composite curves for various phases have been constructed. Table 3 gives characteristic values for

TABLE 2

Magnification for Continuous Sinusoidal Waves of Selected Periods Recorded at Pasadena, September to December, 1957

Period (T)	Magnification for:		
	Long-period Press-Ewing seismographs	Long-period Benioff seismographs	Short-period Benioff seismographs
sec.			
1	80	2,000	14,000
2	180	2,000	5,000
5	800	1,000	400
10	2,000	500	60
20	4,000	250	

travel times obtained in this way. No indication has been found of deviations of individual observations beyond the limits of expected errors in travel times of the phases under investigation.

Sources of Errors

Errors in the travel times of table 3 may result from errors in the assumed locations, origin times, and focal depths of the shocks used. These errors may be appreciably greater than is frequently assumed on the basis of probable errors assigned to shocks by their investigators. Most epicenters listed in table 1 are probably correct within one degree. Errors in their location affect our calculated epicentral distances for a given shock by about the same amount at all stations and thus do not result in noticeable scattering of the travel times. For most phases and epicentral distances involved here, an error of one degree in the component of the distance in the epicenter-to-station direction produces errors of between 2 and 4 seconds in the resulting travel times.

Probably few errors in the assumed origin times exceed 5 seconds. In a given shock such errors affect all calculated travel times by the same amount. In the range of distances given in table 1, errors of ten km. in the assumed focal depth produce errors of about 2 seconds in the travel times of PKIKP, PKIKS, and PKS in shallow shocks and of about 1 second for the deepest shocks when the observed travel times

[2] Figures have been drafted by Mr. L. Lenches. Figure 4 has been arranged by Mr. R. Gilman, and figure 5 by Mr. Lenches.

are reduced to times for zero depth. For SKP and SKIKP the corresponding errors are about 3 seconds for shallow shocks, and about 2 seconds for deep shocks. While errors exceeding 30 km. in our assumed depths are not likely, the resulting errors in individual travel times reduced to zero depth possibly reach 10 seconds in extreme instances.

There are, in addition, the usual errors such as incorrect identification of the beginning of a phase, errors in time corrections, and errors from misinterpretation of phases arriving in short succession.

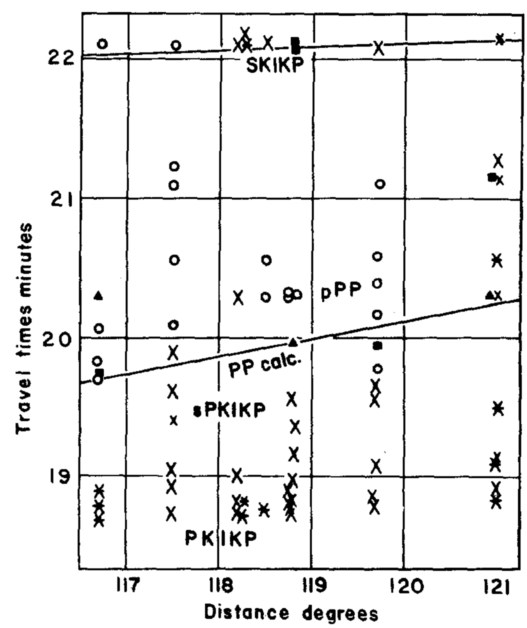

Fig. 3. Travel times observed in earthquake of February 22, 1954, $12^h\ 03^m\ 06^s$, h = 140 km. (table 1). Symbols as in figure 1.

Discussion of the New Observations of PKIKP

PKIKP has apparent angles of incidence of less than 20° and is therefore mainly recorded by vertical components. No agreement has been reached about the epicentral distance at which the travel-time curve of the nondiffracted PKIKP begins. Denson (1952) has observed that its amplitude increases appreciably at distances near 120° and has suggested that this may mark the beginning of PKIKP. Figure 1 indicates that at distances less than 115°, but not at greater distances, arrival times of many small waves with scattering travel times have been measured approximately at the time expected for PKIKP. At distances smaller than 115° no phase exists which beyond reasonable doubt is PKIKP. However, at distances greater than 115° the beginning of PKIKP is so clear that the author has unconsciously disregarded very small waves preceding PKIKP.

There is a possible lining up of travel times from about $18^m\ 30^s$ at 108° to about $18^m\ 50^s$ at 116°. These may belong to diffracted PKIKP waves, while many of the small waves at distances less than 115° and small short-period waves following the beginning of PKIKP at greater distances (figs. 4, 5, A and C) may well be produced by scattering (compare Tatel, 1954; Tatel and Tuve, 1958).

TABLE 3

ADOPTED TRAVEL TIMES (t) FOR ZERO FOCAL DEPTH

(Θ = epicentral distance in degrees. T = period.)

Θ	t, min:sec			
	PKIKP		SKP	SKIKP
	$T = 1\pm$ sec.	$T \geqq 2$ sec.		
117	....	18:48	....	....
118	....	51	....	22:31
119	....	53	....	33
120	....	18:56	....	22:35
121	....	58	....	36
122	....	19:01	....	38
123	....	03	....	39
124	18:53	05	....	40
125	18:55	19:07	22:19	22:42
126	57	08	23	43
127	59	10	26	45
128	19:01	12	29	46
129	04	14	33	48
130	19:06	19:16	22:36	22:49
131	08	18	40	50
132	10	19	43	52
133	12	21	47	54
134	14	23	50	56
135	19:16	19:25	22:53	22:57
136	18	27	56	59
137	20	29	59	23:01
138	23	31	23:03	03
139	25	33	06	04
140	19:27	19:35	23:09	23:06
141	29	36	12	07
142	31	38	16	09
143	33	39	19	10
144	35	41	....	12

The periods of PKIKP are relatively short at all distances, in contrast to those in P and PP. Periods of 1 to 2 seconds prevail by far in PKIKP, and periods exceeding 4 seconds are rare at distances at least as great as 140°. On the other hand, the prevailing periods in the diffracted P increase with increasing distance, and periods of less than 5 seconds are usually missing at distances greater than 120°, where P is rarely recorded by short-period instruments. The periods of PP do not change noticeably with distance; periods between 1 and 30 seconds have been measured at distances at least from 40° to 150°.

Several successive impulses of PKIKP have been recognized by many investigators (compare Gutenberg, 1957*a*). The periods observed in the earliest impulse are usually noticeably shorter than those of the later (compare figs. 4 and 5, C). Neither in records of deep nor in those of shallow shocks could the early waves (a) be found beyond doubt at epicentral distances of less than about 124° (compare fig. 4).

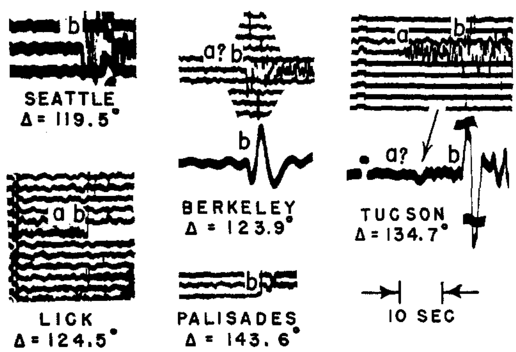

Fig. 4. PKIKP phases (a) and (b) recorded by vertical seismographs, April 16, 1957, h = 600 km. (table 1). Seattle record from Sprengnether seismograph; Lick and Palisades records from short-period Benioff seismographs; Berkeley and Tucson from short-period Benioff seismographs on top, from long-period below. For selected PKIKP-phases recorded at southern California stations see Gutenberg (1957*a*, fig. 1). The time scale is the same on all records of figure 4; on the original seismograms 1 mm. corresponds to 1 sec. on short-period instrument records, to 2 sec. on long-period.

Discussion of SKP, SKIKP, PKS, and PKIKS

The apparent angles of incidence of SKP, SKIKP, PKS, and PKIKS at the earth's surface are usually less than 20°. Consequently, those ending with P are recorded relatively large in vertical components, those ending with S, in horizontal components (fig. 5, D, E). Except for SKP and PKS near their focal points at distances of about 130°, all four are usually relatively small. This results partly from the fact that in SKP and SKIKP the SH-component of S is totally reflected when S arrives in the mantle at the core boundary, while in PKS and PKIKS no SH-components can be generated when the waves arrive at the core boundary from inside the core. Consequently, PKS and PKIKS should theoretically contain only a nearly horizontal SV-component (compare fig. 5, D). Moreover, S-waves having periods of less than 4 seconds are strongly attenuated when they pass through the outer portion of the mantle (Gutenberg, 1958, table 3; Båth, 1958), while waves with longer periods seem to undergo high attenuation in the transition zone between the outer and the inner core, as indicated by PKIKP. Consequently, SKIKP is rarely well recorded in shallow shocks. In shocks originating at intermediate and great depths, short-period S-waves may reach the core. The periods of the resulting

SKIKP-waves usually do not exceed 3 seconds (example in fig. 5, B). Similarly, SKIKS is rarely large; moreover, up to distances of about 130° it follows SKS within a few wave lengths.

The time interval between SKP and PKS increases from zero for surface foci to about 1 minute for shocks at a depth of 700 km., so that PKS- and PKIKS-phases

TABLE 4

Adopted Travel Times between Points of the Surface of the Core

(Θ = distance in degrees. T = period.)

Travel time, min:sec				
Θ	First branch	Θ	Second branch	
			$T\sim 1$ sec.	$T \geq 2$ sec.
5	0:38	95	....	9:53
10	1:16	100	9:52	10:04
15	1:53	105	10:02	10:13
20	2:29	110	10:13	10:22
25	3:05	115	10:23	10:31
30	3:41	120	10:34	10:40
35	4:16	125	10:44	10:48
40	4:50	130	10:53	10:56
45	5:22	135	11:02	11:04
50	5:52	140	....	11:11
55	6:20	145	....	11:17
60	6:46	150	....	11:24
65	7:10	155	....	11:30
70	7:35	160	....	11:35
75	7:58	165	....	11:40
80	8:20	170	....	11:43
85	8:41	175	....	11:44
90	9:01	180	....	11:45
95	9:21			
100	9:40			
105	9:57			
110	10:12			
115	10:26			
120	10:39			
125	10:53			
130[a]	11:05			

[a] Only for $T \geq 2$ sec.

are clearly separated from SKP and SKIKP respectively only in records of intermediate and deep shocks (fig. 5, B, D, E). After further research on the time intervals PKS–SKP and PKIKS–SKIKP as function of focal depth and epicentral distance these intervals may be useful in the determination of focal depths.

SKP and PKS, neither of which has penetrated the inner core, have frequently greater periods than SKIKP and PKIKS (compare fig. 5, D and E, with 5, B).

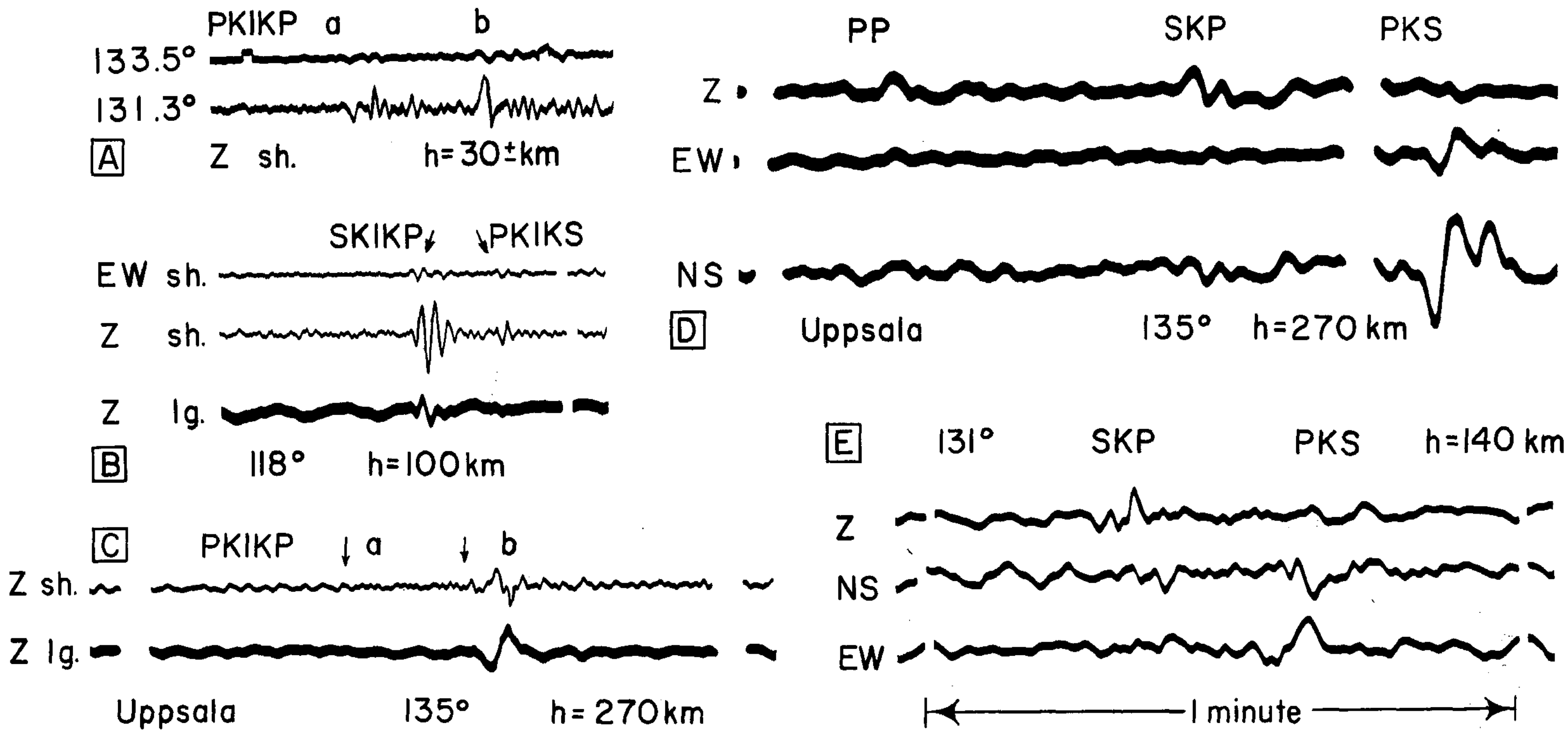

Fig. 5. (A) PKIKP, recorded on July 9, 1957 (table 1), by short-period Benioff vertical instruments at Palomar (top) and Isabella (bottom). (B) SKIKP and PKIKS recorded at Pasadena on January 1, 1954; sh. = short-period, lg. = long-period Benioff seismograph. (C) PKIKP recorded by short-period Grenet (sh.) and long-period Benioff (lg.) vertical seismographs at Uppsala on August 9, 1956 (see "Materials"). (D) SKP and PKS, arriving from north, recorded by long-period Benioff seismographs on August 9, 1956. (E) SKP and PKS recorded by long-period Benioff seismographs at Pasadena, April 10, 1956. The time scale is the same for all records of figure 5. For scale on original seismograms see figure 4.

Travel Times between Points on the Surface of the Core

In calculating travel times for the core (table 4) the following combinations for surface foci have been used: PKP − PcP; PKIKP − PcP; SKP − ScP (travel times of SKP and PKS are equal); SKIKP–ScP; SKS–ScS; SKIKS–ScS; ½(PKPPKP)–PcP; ½(PKIKPPKIKP)–PcP; ½(PKKP–PcP). Travel times t and values for $dt/d\Theta$ for PcP, ScP, and ScS have been taken from Jeffreys and Bullen (1940, pp. 37 and 39). Travel times resulting from SKS–ScS are frequently longer than those based on other phases, perhaps as a consequence of relatively late readings for the beginning of SKS. Otherwise, individual travel times calculated for the core rarely deviate by more than 2 seconds from the data given in table 4.

No observations are available to calculate travel times in the core for distances from 0° (where $t = 0$) to 22°. Between 22° and 83° all data are based on SKS (Nelson, 1952, 1954; Gutenberg, 1955). Starting at 83°, data from PKKP (Gutenberg, 1955) are added. For distances greater than 90° there are, in addition, data from SKP of Forester (1953, 1956). Data for distances between 115° and 130° of the first branch result mainly from SKP (Forester, 1953, 1956), PKP (Denson, 1950, 1952), and PKKP (Gutenberg, 1955).

For distances less than 130° the two curves of the second branch are based on data of the present paper with addition of data for PKIKPPKIKP (Gutenberg, 1955). Between 130° and 140°, mainly PKIKPPKIKP, PKIKKIKP, and PKIKP have been used; travel times for distances between 150° and 175° are based on SKIKS (Nelson, 1952, 1954) and PKIKP (Gutenberg and Richter, 1934, 1943).

The Velocity in the Core

For the calculation of the velocity the following equations have been used for rays starting and ending at the surface of the core (radius 3,473 km.):

$$\log r_s = 3.5407 - 0.0024127 \int_0^{\Theta_s} \cosh q \, d\Theta \tag{1}$$

$$v_s = 0.017453 \, r_s \, \bar{v}_s \tag{2}$$

where v_s is the velocity in km/sec. at the deepest point of the ray which arrives at the surface of the core at a selected distance Θ_s in degrees, r_s is the radius to this deepest point in km., $\bar{v}_s$ is the apparent velocity in degrees per second at the distance Θ_s, and q is the ratio of the fixed apparent velocity at Θ_s to the apparent velocities at the distances from $\Theta = 0$ to $\Theta = \Theta_s$. For reversed segments the corresponding portion of the integral is negative (Slichter, 1932). Usually, it is preferable to calculate $1/\bar{v}_\Theta$ (seconds per degree), then to find q as the product of the fixed $\bar{v}_\Theta$ at Θ_s and the variable $(1/\bar{v}_\Theta)$ (from $\Theta = 0$ to $\Theta = \Theta_s$), and finally to divide by $1/\bar{v}_s$ in equation (2).

A smoothed curve for the resulting velocities in the core is reproduced in figure 6. In addition to the beginning of the curve, which is based on interpolated travel times, the velocities are somewhat uncertain for the transition zone between the outer and the inner core. The travel-time curve of waves through the core consists of at least two branches (table 4). However, it is difficult to find the accurate end of the first branch (which was assumed to be at $\Theta = 125°$ for short-period waves, at 130° for long-period waves) and of the beginning of the second (assumed at 100° and 95° respectively on the basis of fig. 1). Moreover, assumptions have to be made for a reversed segment connecting these two points. This segment is a portion of the travel-time curve for waves through the core, if the velocity increases rapidly but continuously with depth; however, it is a part of the travel-time curve of the waves reflected at the inner core, if the increase in velocity is sudden (compare for example Bullen, 1953, pp. 112 ff.; Slichter, 1932). No observations are available for this connection; theoretical requirements limit the assumptions for the corresponding travel

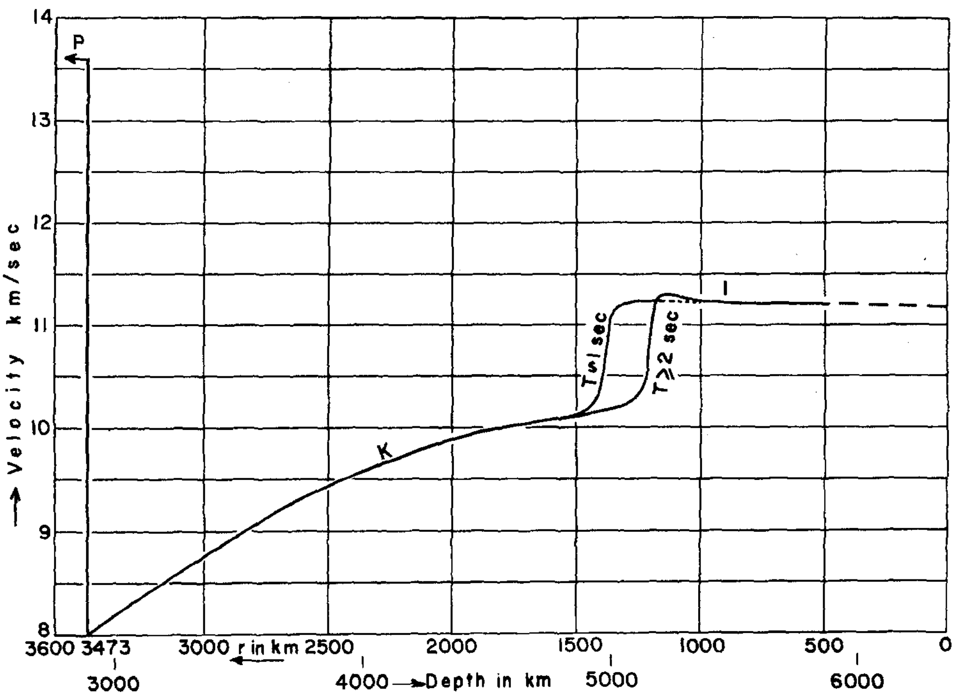

Fig. 6. Velocity of longitudinal waves in the earth's core.

times. Even with these restrictions the results differ somewhat, depending on the assumptions. Additional complications are introduced by the dispersion of the waves, indicated by the observations of PKIKP. However, there is little doubt about the relationship between the velocities of the short-period to those of the long-period waves.

Finally, the velocity near the earth's center is less certain than the average as it affects relatively little the travel times of PKIKP approaching $\Theta = 180°$. No other phase can be used to find the velocity near $r = 0$.

The Structure of the Earth's Core

Gutenberg (1957*a*) has suggested that the difference in velocity for short and long longitudinal waves in the transition zone from the outer to the inner core results from dispersion and that the apparent "radius" of the inner core is greater for waves having lengths of 10 km. or less than for noticeably longer waves. These conclusions have been strengthened by the present research (fig. 6). Moreover, in the interim

Gutenberg (1957*b*) has found that in P- and S-waves of earthquakes recorded at distances between 20° and 100° a very few distinct periods prevail. This explains why we do not find in seismograms a gradual increase in periods of PKIKP, but frequently at least two distinct phases with only short waves in the first (a, in figs. 4 and 5, A, C) while the last (b) includes waves with longer periods. Occasionally, additional waves with intermediate periods are visible (compare the wave marked by the arrow in fig. 4). In SKIKP and PKIKS waves having periods of 1 second or less are nearly absent, and therefore normally only waves corresponding to the phase (b) of PKIKP are observed.

Kuhn and Vielhauer (1953) have pointed out that dispersion of elastic waves is to be expected in a transition zone between liquid and solid material of the same composition, since according to their experiments and to theoretical conclusions in material at a temperature near its melting point the bulk modulus depends on the wave periods. On the basis of their findings Gutenberg (1957*a*) has concluded that the dispersion in PKIKP probably indicates no appreciable difference between the material in the outer and the inner core, but a transition from a "liquid" state in the outer core to one with much higher viscosity in the inner core. Other evidence indicating that the inner core may be solid has been summarized by Bullen (1958).

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